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Patentanmeldung Nr.
Patent application no.
Demande de brevet n°
PCT/EP 02/04504

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Sheet 2 of the certificate
Page 2 de l'attestation

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PCT/EP 02/0450

BIDIRECTIONAL ISOLATOR AND OPTICAL DEVICES COMPRISING A BIDIRECTIONAL ISOLATOR

The present invention relates to a bidirectional optical isolating device and to optical devices comprising a bidirectional isolating device.

The use of optical fiber in long-distance transmission of voice and/or data is now common. As the demand for data carrying capacity in the transmission of voice and/or data continues to increase, there is a continuing need to augment the amount of actual fiber-optic cable being used as well as to utilize the bandwidth of existing fiber-optic cable more efficiently. One of the ways in which this last task may be performed is through the practice of wavelength division multiplexing (WDM) in which multiple information channels are independently transmitted over the same fiber using multiple wavelengths of light. In this practice, each light-wave-propagated information channel corresponds to light within a specific wavelength range or "band". To increase data carrying capacity in a given direction, the number of such channels or bands should be preferably increased.

Additionally, it is desirable to use existing fiber for bidirectional communications. Through the use of WDM, a single optical fiber may be used to transmit, both simultaneously and independently, eastbound (northbound) as well as westbound (southbound) data. However, since all of the channels preferably reside within specific, low-loss wavelength regions determined by the properties of existing optical fiber or of other devices in the transmission system, such as optical amplifiers, increased channel capacity requires increased channel density. Thus, as the need for increased data carrying capacity escalates, the demand on WDM optical components —to transmit increasing numbers of more closely spaced channels with no interference or "crosstalk" between them and over long distances-- becomes more severe.

For example, in a first typical channel allocation scheme, westward propagating channels may have a center wavelength comprised in a first, relatively short ("blue"), wavelength band and eastward propagating channels may have a center wavelength comprised in a second, relatively long ("red"), wavelength band. The "blue" wavelength band and the "red" wavelength band occupy separate

wavelength regions wholly contained in the optical transmission window centered near a wavelength of about 1.55 μm.

In a second typical channel allocation scheme, westward and eastward propagating channels may respectively have a center wavelength spaced by a predetermined channel spacing "d". However, the center wavelengths of the eastward propagating channels are between the center wavelengths of the westward propagating channels (interleaved channels). For example, "even" channels λ_2, λ_4, λ_6, λ_8 may be westward propagating and "odd" channels λ_1, λ_3, λ_5, λ_7 may be eastward propagating.

Clearly, other channel allocation schemes may be used for implementing bidirectional optical communications.

Back reflections of optical communications signals are a significant problem in optical systems. Such reflections may be generated at junctions between optical system components and/or may be due to scattering occurring along an optical fiber. They typically induce noise and distortion, which can significantly reduce and deteriorate the performance of a component and/or of the overall system. In particular, the back reflections are an acute problem in systems which include a gain element, such as an optical amplifier (either a rare earth doped amplifier or a semiconductor amplifier). In fact, reflections which travel back into the amplifier may be amplified and increase the error rate of the system or can cause the amplifier to randomly oscillate or begin to lase.

Optical isolators have been employed to inhibit reflections. To prevent oscillations or gain fluctuations occurring in the amplifier, isolators are usually employed at least at one end of an amplifier. Isolators are configured to allow optical signals to pass in one direction, but stop or inhibit signals traveling in the opposite direction.

In view of the difficulties caused by back reflections and the need to inhibit them with unidirectional isolators, gain elements are restricted to operating on signals transmitted in one direction. This imposes an increased cost burden on a system when gain is required in both directions of transmission on an optical fiber line, as in bidirectional optical communications.

Optical isolators are also of benefit for applications exploiting Raman amplification. US patent n. 5,673,280, to Lucent Technologies, discloses a low noise optical fiber Raman amplifier comprising an upstream and a downstream length of silica-based amplifier fiber, of combined length being more than 200 m, typically more than 1 km, with an optical isolator disposed between the upstream and downstream lengths of amplifier fiber, such that the passage of backscattered signal radiation from the latter to the former is substantially blocked. In preferred embodiments, counter-propagating pump radiation is coupled into the downstream length of amplifier fiber, and wavelength-selective couplers are provided for shunting the pump radiation around the optical isolator.

The Applicant observes that also in the application disclosed in the '280 patent there are signals that propagate in two opposite directions in the same fiber, i.e. the signal radiation amplified in the Raman amplifier fiber lengths and the counter-propagating pump radiation causing Raman amplification. According to the Applicant, the use of a shunt circuit for allowing the counter-propagating pump radiation to propagate in the direction inhibited by the optical isolator may not represent an optimal solution, as it necessitates at least two more components, i.e. the wavelength selective couplers, increasing costs, complexity of the device and attenuation on the signal. The isolation requirements of the wavelength-selective couplers, which should be high in order to guarantee that signal and/or pump radiation are not lost in the shunt circuit, may be a further source of increasing costs.

Components suitable for allowing passage of optical signals of one wavelength band in one direction of travel and of optical signals of another wavelength band in the opposite direction of travel (and blocking back reflections in both cases) have already been proposed. For example, patent application WO 93/25014, to Telstra Corporation Limited, discloses a bidirectional isolator including, in a first configuration, two wavelength selective elements, a forward isolator part and a backward isolator part. The isolator parts are connected parallel between the wavelength selective elements. The wavelength selective elements are connected to respective optical fiber lines which carry optical signals on two wavelength bands, λ_1 for one direction (forward direction) and λ_2 for the opposite direction (backward direction). Allocating forward and reverse wavelength transmission bands which do not overlap allows the isolator to separately isolate the signals of

the different bands using the forward and backward isolator parts. The wavelength selective elements, which may be prisms, dichroic mirrors, holograms, dichroic couplers or gratings, split the incoming signals on the fiber lines into two paths. One path is for signals of wavelength band λ_1 which are passed to the forward isolator part, and the second path is for signals of wavelength band λ_2 which are passed to the backward isolator part. The forward isolator part only transmits signals traveling from first wavelength selective element to the second wavelength selective element and cancels signals received from the second wavelength selective element. Similarly, the backward isolator part only transmits signals traveling from the second wavelength selective element to the first wavelength selective element and cancels signals traveling from the first wavelength selective element. Therefore the isolator cancels reflections of the wavelength band λ_1 traveling in the backward direction and cancels reflections of the wavelength band λ_2 traveling in the forward direction. In a second configuration, the bidirectional isolator of the patent application WO 93/25014 includes two directional elements, such as for example three- or four-port optical circulators, in place of the wavelength selective elements. The forward and backward isolator parts are replaced by optical filters. The first filter inhibits signals of the wavelength band λ_2 and passes signals of the wavelength band λ_1, whereas the second filter inhibits signals of the wavelength band λ_1 and passes signals of the wavelength band λ_2. In a third configuration, the bidirectional isolator of the patent application WO

In a third configuration, the bidirectional isolator of the patent application WO 93/25014 includes two wavelength selective elements, two spatial walk-off polarizers, a polarization dependent isolator and three judiciously placed half-wave plates. The wavelength selective elements are connected to first and second optical fiber lines, respectively, which carry signals of the forward wavelength band λ_1 and of the backward wavelength band λ_2. The wavelength selective elements split both bands into two paths, a forward path and a backward path. The polarizers split the signals on the two paths into four paths, two paths for the forward wavelength band λ_1 and two paths for the backward wavelength band λ_2. The polarizers break the signals of the two paths into two polarized orthogonal components for transmission on the four paths. The half-wave plates rotate a polarized component by 90°. The first half-wave plate rotates the vertical components of the λ_1 band signals and the horizontal components of the λ_2 band signals between the first polarizer and the isolator. The second and third half-wave

plates rotate the horizontal components of the λ_1 band signals and the vertical components of the λ_2 band signals between the isolator and the second polarizer. The polarization dependent isolator includes for each wavelength band respective polarizers and Faraday rotators.

According to the Applicant, the configurations of the bidirectional isolator disclosed in WO 93/25014 are quite complicated as they always require at least two different optical paths for each of the two wavelength bands to be isolated, as well as a doubling of all the needed components. This further increases manufacturing costs of the bidirectional isolator.

US patent n. 5,912,766, to Telstra Corporation Limited, discloses an optical isolator comprising two polarizer means, two input/output ports formed respectively on said polarizer means, and optical rotator means disposed between said polarizer means, said optical rotator means including Faraday rotator means and being selectively configured so that the isolator performs one of a plurality of isolator functions. The wavelength dispersion characteristics of said optical rotator means may determine said one of said isolator functions for at least two wavelength bands. In a disclosed embodiment, the isolator includes first and second input ports formed at the junction of respective graded-index (GRIN) lenses and spatial walk-off polarizers (SWPs). The isolator also includes a Faraday rotator and a reciprocal optical rotator disposed between the SWPs, such that all of the components form an in-line series assembly. The Faraday rotator and the reciprocal optical rotator are configured so as to provide one of a plurality of isolator functions for the isolator for two or more wavelength bands. For example, if λ_1 and λ_2 denote first and second wavelength bands, the functions may comprise isolate signals of λ_2 in one direction and isolate signals of λ_1 in the opposite direction, so that the isolator is allowed to function as a bidirectional isolator. The length of the Faraday rotator, which governs the length of the light transmission path therethrough, is selected so as to provide the rotator with a wavelength dispersion characteristic which gives rise to the desired polarization component rotation $\pm m\ 180°$, where m is a non-negative integer. Similarly, the optical path length of the reciprocal optical rotator is selected to provide a wavelength dispersion characteristic which achieves the desired effective rotation

±m 180°. The reciprocal optical rotator may comprise half-wave plate or optically active material.

EP patent application n. 1,079,249, to JDS Uniphase Inc., discloses a bidirectional wavelength dependent optical isolator having two thick birefringent waveplates, having their optical axes oriented such that their birefringent axes are oriented differently, and a non-reciprocal element. The thick plates have a periodic wavelength response with polarization. In operation, even channels are passed while odd channels are blocked in a first direction from port 1 to port 2 and conversely, even channels are blocked and odd channels are passed in a second opposite direction from port 2 to port 1. In a disclosed embodiment, the first thick plate is half the length of the second thick plate and is oriented at 45° to vertically polarized incoming light and the second thick plate is oriented at 105° to the vertically polarized incoming light.

The Applicant observes that an isolator according to EP 1,079,249 may be not suitable for applications needing a channel allocation scheme different from an interleaved one.

WO patent application n. 01/35131, to Avanex Corporation, discloses a bidirectional polarization independent optical isolator simultaneously transmitting two separate signal rays in opposite forward directions and simultaneously suppressing backward transmission of each signal ray in its respective reverse direction. The separate signal rays may comprise either two wavelength bands completely separated by wavelength (band bidirectional isolator) or two sets of wavelengths, such that wavelengths of the two signal rays are interspersed in alternating fashion (interleaved bidirectional isolator). The bidirectional polarization independent isolator includes a birefringent polarization separation/combining element, a reciprocal optical rotation element, a lens, a reflective element, and a reciprocal optical rotation element. The reflective element comprises either a mirror/waveplate assembly or a non-linear interferometer. More particularly, the mirror/waveplate assembly is disclosed in connection with the band bidirectional isolator and the non-linear interferometer is disclosed in connection with the interleaved bidirectional isolator. Four fibers or optical ports are optically coupled to the isolator and may be configured such that either single-stage bi-directional

isolation is accomplished for each of two fiber transmission lines or double stage bi-directional isolation is accomplished on a single fiber transmission line.

The Applicant has tackled the problem of realizing a bidirectional isolating device being capable of passing and isolating signal radiations having different wavelengths traveling in opposite directions, the isolating device having low losses, high facility of manufacturing and compactness. According to the Applicant, as different applications may require different schemes for the arrangement of propagation directions versus wavelength, as seen before (for example, the opposite propagating signals may belong to mutually exclusive wavelength ranges or may have interleaved wavelengths), the components included in the isolating device should guarantee that, given a specific scheme, they may be simply reconfigured in order to allow the isolating device to comply with the specific scheme, without changing the type of device or the type of components included therein.

The Applicant has found that such problem may be solved by an isolating device exploiting a Faraday rotator and a stack of birefringent elements (e.g. waveplates) having their optical axes oriented so as to obtain a half wave retardation for the group of signals propagating in the first direction and a full wave retardation for the group of signals propagating in the second, opposite direction. The orientation of the optical axes of the birefringent elements may be accomplished so that the isolating device may comply with any allocation scheme for the opposite propagating signals. Further, the Faraday rotator and the stack of birefringent elements may be easily packed together with polarization beam splitters, so as to obtain a very compact polarization independent device.

In a first aspect, the invention relates to an optical isolating device, adapted for allowing passage of a first group of optical signals having a first group of wavelengths in a first direction and for blocking passage of said first group of optical signals in a second direction, opposite to said first direction, and adapted for allowing passage of a second group of optical signals having a second group of wavelengths in said second direction and for blocking passage of said second group of optical signals in said first direction, said optical isolating device comprising:

- first and second polarizers;
- a nonreciprocal polarization rotator, arranged for rotating a polarization of a signal of substantially 45° ± k·90°, wherein k is a non-negative integer, in both said first and second directions;
- a reciprocal polarization rotator;

characterized in that

- said reciprocal polarization rotator comprises a plurality of birefringent elements, having substantially the same thickness and being oriented so as to obtain a half wave retardation for said first group of signals and a full wave retardation for said second group of signals.

In a first embodiment said first group and said second group of signals may have wavelengths included in mutually exclusive wavelength ranges.

In a first example, said first group of signals may have wavelengths higher than or equal to 1525 nm and lower than or equal to 1630 nm, and said second group of signals may have wavelengths higher than or equal to 1410 nm and lower than or equal to 1510 nm.

In a second example, said first group of signals may have wavelengths higher than or equal to 1545 nm and lower than or equal to 1565 nm, and said second group of signals may have wavelengths higher than or equal to 1525 nm and lower than or equal to 1535 nm.

In a second embodiment, said first group and said second group of signals may have interleaved wavelengths.

Preferably, said birefringent elements may have a thickness variation of less than or equal to 1%.

In a preferred embodiment, said plurality of birefringent elements may be disposed so that elements having a lower thickness alternate to elements having a higher thickness.

Said birefringent elements may advantageously comprise a material having a birefringence higher than or equal to $1 \cdot 10^{-2}$.

Advantageously, said plurality of birefringent elements introduces an overall attenuation lower than 0.5 dB on both said first and second group of signals.

In a second aspect, the invention relates to an optical amplifier comprising:

- at least a first optical amplifying medium;
- a pumping system suitable for furnishing a pumping power and for providing such pumping power to said first optical amplifying medium;
- an optical isolating device according to the above.

Said first optical amplifying medium may comprise a rare-earth doped fiber and said pumping system may comprise at least one pump laser and at least one WDM coupler, one end of said rare-earth doped fiber being connected to a first port of said WDM coupler and said pump laser being connected to a second port of said WDM coupler.

Said optical amplifier may further comprise at least a second optical amplifying medium, said pumping system being suitable for providing said pumping power also to said second amplifying medium, said optical isolating device being disposed between said first and second amplifying medium.

For example, said optical amplifier may be suitable for transmitting said first group of signals in said first direction, and:

- said first optical amplifying medium may comprise a first length of Raman-active optical fiber;
- said second optical amplifying medium may comprise a second length of Raman-active optical fiber, downstream from said first length of Raman-active optical fiber with respect to said first direction;
- said pumping system may comprise at least one pump laser adapted for emitting a pumping radiation having a wavelength included in said second group of wavelengths, said pumping radiation being adapted for

causing Raman amplification of said first group of signals in said first and said second lengths of Raman-active optical fiber;

- said pumping system may further comprise at least one WDM coupler, one end of said second length of Raman-active fiber being optically connected to a first port of said WDM coupler and said at least one pump laser being optically connected to a second port of said WDM coupler, so that said pumping radiation may propagate from said second length of Raman-active optical fiber to said first length of Raman-active optical fiber.

Further features and advantages of the present invention will be better illustrated by the following detailed description, herein given with reference to the enclosed drawings, in which:

- Figure 1 schematically shows the structure and the functioning in a forward and in a backward direction of a preferred embodiment of a bidirectional isolating device according to the invention;
- Figure 2 schematically shows a plurality of birefringent waveplates having thickness D and axes of polarization (dashed lines) differently oriented versus a predetermined polarization direction (continuous lines);
- Figure 3 schematically shows a preferred embodiment of a bidirectional optical amplifier using bidirectional isolators according to the invention;
- Figure 4 schematically shows a preferred embodiment of a double stage amplifier exploiting counter-propagating Raman amplification, using a bidirectional isolator according to the invention;
- Figures 5a and 5b show the results of a first simulation performed by the Applicant for an exemplary stack of birefringent waveplates;
- Figure 6 shows how the plot of fig.5b may modify its profile by changing the thickness value of the birefringent waveplates;
- Figure 7 shows the result of a second simulation performed by the Applicant with stacks of birefringent waveplates having slightly varying thickness.

Fig.1 schematically shows the structure and the functioning in a forward and in a backward direction of a preferred embodiment of a bidirectional isolating device according to the invention. More particularly, fig.1 schematically shows the structure and the functioning in a forward and in a backward direction of a preferred embodiment of a bidirectional isolator 10. The isolator 10 comprises two GRIN lenses 11, 16, two polarizers 12, 15, a wavelength selective reciprocal polarization rotator 13 and a non-reciprocal Faraday rotator 14. The wavelength selective reciprocal polarization rotator 13 and the non-reciprocal Faraday rotator 14 are optically arranged between the two polarizers 12, 15.

The GRIN lenses 11 and 16 guarantee the focusing on the input/output ports 12a and 15a of the polarizers 12 and 15 of light propagating on optical paths 17a and 17b. Suitable components other than GRIN lenses may be used for such purpose. The optical paths 17a and 17b may be exemplarily optical fibers, typically single mode optical fibers.

In the embodiment shown in fig.1, the polarizers 12 and 15 are adapted to split light having any polarization along two separate optical paths, in which perpendicular polarizations are propagated. In the same manner, the polarizers 12, 15 allow recombination on a same optical path of light propagating into two separate optical paths in perpendicular polarizations. To such purpose, polarization beam splitters (or walk-off polarizers), suitably oriented, may be used. In particular, they may be used in the optical isolator 10 in order to make it independent on polarization, which may be advantageous for use with typical, non-polarization maintaining optical fibers. If polarized light is used, polarization beam splitters 12 and 15 may be substituted by simple polarizing waveplates, suitably oriented, or other polarizers.

The reciprocal wavelength selective polarization rotator 13 comprises a stack of birefringent elements, having their axes of polarization oriented so that a first group of polarized signals having a first group of wavelengths does not undergo any rotation (or undergoes a rotation of ± n180°, wherein n is a non-negative integer), whereas a second group of polarized signals having a second group of wavelengths may undergo rotation of their axes of polarization of 90° ± m180°, wherein m is a non-negative integer. The polarization rotator 13 is reciprocal, in the sense that it changes the rotation direction of the polarization of the incoming

signal (clockwise or counterclockwise) according to the direction of the incoming light (forward or backward). The first group of signals and the second group of signals may have wavelengths disposed according to any allocation scheme: for example, the first group of signals may have wavelengths comprised in a first wavelength range and the second group of signals may have wavelengths comprised in a second wavelength range, the first and the second wavelength ranges being mutually exclusive; as another example, the first and the second group of signals may have interleaved wavelengths. According to the allocation scheme to be accomplished, the number and the orientation of the axes of polarization of the birefringent elements used in the polarization rotator 13 may be determined, according to a technique that will be described in the following.

The Faraday rotator 14 rotates the polarization of any polarized incoming signal substantially of an angle of 45° ± k 90°, wherein k is a non-negative integer. Small variations of the above angle may be tolerated in dependence of the isolation requirements. The Faraday rotator may be of any kind, either comprising a single rotation element or a plurality of rotation elements, either in a signal single-pass or in a signal multi-pass configuration, so as to provide an overall rotation of 45° ± k 90°. It is non-reciprocal, in the sense that the direction of rotation (clockwise or counterclockwise) does not change with the changing of the direction of the incoming signal.

The bidirectional isolator 10 of fig.1 may be packaged by advantageously contacting the various components to each other, such that all of the components form an in line series compact assembly. Transparent glues may be used in order to improve the steady positioning of the various components.

Fig.1 also shows the functioning of the bidirectional isolator 10, by considering a first group of signals propagating in a forward direction (upper figure) and a second group of signals propagating in a second direction (lower figure). Let λ_1 be the wavelength of a signal belonging to the first group of signals. Let λ_2 be the wavelength of a signal belonging to the second group of signals.

In a forward direction (upper figure), signals having wavelength λ_1 should be allowed to propagate whereas possible back-reflection of radiation having wavelength λ_2 propagating in forward direction should be blocked. Let's consider a

signal of wavelength λ_1 and a back-reflected signal of wavelength λ_2, both propagating in forward direction on the optical path 17a, both having random polarization. The first GRIN lens 11 focuses both signals on the first input port 12a of the first polarization beam splitter 12. The first polarization beam splitter 12 separates the polarizations of the two signals, so that the horizontal polarizations of both signals exit from the first output port 12c and the vertical polarizations of both signals exit from the second output port 12d of the first polarization beam splitter 12. The two polarizations of both signals propagate on the two separate optical paths 17c and 17d. The polarization rotator 13 leaves unchanged the polarization of the signal having wavelength λ_1 and rotates of 90° the polarization of the signal having wavelength λ_2. For example, let's suppose that the polarization rotator 13 rotates the polarization of the signal having wavelength λ_2 in clockwise direction as such signal propagates forward. Thus, on the optical path 17c the signal having wavelength λ_1 exits from the rotator 13 with a vertical polarization, whereas the signal having wavelength λ_2 exits from the rotator 13 with a horizontal polarization. On the contrary, on the optical path 17d the signal having wavelength λ_1 exits from the rotator 13 with a horizontal polarization, whereas the signal having wavelength λ_2 exits from the rotator 13 with a vertical polarization. The Faraday rotator 14 rotates the polarization of both signals on both optical paths 17c, 17d of the same angle independently of the propagation direction of the incoming signal, for example 45° clockwise. Thus, on the optical path 17c the signal having wavelength λ_1 exits from the Faraday rotator 14 with a polarization oriented at +45°, whereas the signal having wavelength λ_2 exits from the Faraday rotator 14 with a polarization oriented at –45°. On the optical path 17d the signal having wavelength λ_1 exits from the Faraday rotator 14 with a polarization oriented at –45°, whereas the signal having wavelength λ_2 exits from the Faraday rotator 14 with a polarization oriented at –135°. The two signals propagating on the two separated optical paths 17c and 17d, with polarizations according to the above, thus arrive to the first and second output ports 15c, 15d of the second polarization beam splitter 15. The second polarization beam splitter 15 is oriented at +45° with respect to the first polarization beam splitter 12, so that it may recombine the signal having wavelength λ_1 on its first input port 15a. Further, it may recombine the back-reflected signal having wavelength λ_2 on its second input port 15b. Alternatively, the two polarizations of the signal having wavelength

λ_2 may not be recombined together. In any case, the back-reflected signal having wavelength λ_2 is separated by the signal having wavelength λ_1, and may be eliminated (e.g., by absorption), whereas the signal having wavelength λ_1 may be allowed to propagate, through the second GRIN lens 16, on the optical path 17b.

In a backward direction (lower figure), signals having wavelength λ_2 should be allowed to propagate whereas possible back-reflection of radiation having wavelength λ_1 propagating in backward direction should be blocked. Let's consider a signal of wavelength λ_2 and a back-reflected signal of wavelength λ_1, both propagating in backward direction on the optical path 17b, both having random polarization. The second GRIN lens 16 focuses both signals on the first input port 15a of the second polarization beam splitter 15. The second polarization beam splitter 15 separates the polarizations of the two signals, so that both signals exit from the first output port 15c with a polarization oriented at +45° and from the second output port 15d with a polarization oriented at -45°. The two perpendicular polarizations of both signals propagate on the two separate optical paths 17c and 17d. The Faraday rotator 14 rotates clockwise the polarization of both signals on both optical paths 17c, 17d of an angle of 45°. Thus, on the optical path 17c both signals having wavelength λ_1, λ_2 exit from the Faraday rotator 14 with horizontal polarization, whereas on the optical path 17d both signals having wavelength λ_1, λ_2 exit from the Faraday rotator 14 with vertical polarization. The polarization rotator 13 leaves unchanged the polarization of the signal having wavelength λ_1 and rotates (counterclockwise, for signals propagating in backward direction) of 90° the polarization of the signal having wavelength λ_2. Thus, on the optical path 17c the signal having wavelength λ_1 exits from the rotator 13 with a horizontal polarization, whereas the signal having wavelength λ_2 exits from the rotator 13 with a vertical polarization. On the contrary, on the optical path 17d the signal having wavelength λ_1 exits from the rotator 13 with a vertical polarization, whereas the signal having wavelength λ_2 exits from the rotator 13 with a horizontal polarization. The two signals propagating on the two separated optical paths 17c and 17d, with polarizations according to the above, thus arrive to the first and second output ports 12c, 12d of the first polarization beam splitter 12. The first polarization beam splitter 12 is oriented so that it may recombine the signal having wavelength λ_2 on its first input port 12a. Further, it may recombine the back-

reflected signal having wavelength λ_1 on its second input port 12b. Alternatively, the two polarizations of the signal having wavelength λ_1 may not be recombined together. In any case, the back-reflected signal having wavelength λ_1 is separated by the signal having wavelength λ_2, and may be eliminated (e.g., by absorption), whereas the signal having wavelength λ_2 may be allowed to propagate, through the first GRIN lens 11, on the optical path 17a.

The wavelength selective reciprocal polarization rotator 13 used in the bidirectional optical isolator 10 according to the invention exploits the principle of the Solc filters. A plurality of birefringent elements having substantially the same thickness are disposed so that their axes of polarization are differently oriented versus a predetermined reference polarization direction (see fig.2). For example, the reference direction may be the horizontal polarization or the vertical polarization of a signal emerging from the first polarizer 12. In preferred embodiments, the birefringent elements may be birefringent waveplates. Alternatively, the birefringent elements may be portions of birefringent optical fiber (see, for example, H.D. Ford, Ralph P. Tatam, *"Birefringent-fiber wavelength filters"*, SPIE Proceedings Vol. 2341 (1994), pp.173-181). The expression "having substantially the same thickness" means, in the framework of the present invention, that the elements of the stack have a maximum thickness variation of 2%, preferably 1%, more preferably 0.6%. The different orientation of the axes of polarization of the birefringent elements allows an energy exchange between orthogonally polarized modes of signal propagating therethrough: such energy exchange depends on the wavelength of the signal, so that the stack of birefringent elements may behave like a full wave retarder for signals having a first group of wavelengths and like a half-wave retarder for signals having a second group of wavelengths, according to a predetermined transfer function. In particular, a periodic transfer function may be chosen. For example, if the first group of wavelengths and the second group of wavelengths belong to mutually exclusive wavelength ranges, respectively a first wavelength range and a second wavelength range, the period of the function may be comprehensive of the first wavelength range, of the second wavelength range and typically of a transition wavelength region between the first and the second wavelength range. The width of such transition region may be low, e.g. 15-20 nm, in dependence of the application. As another example, the first and the second group of wavelengths may correspond to interleaved wavelengths: in such case,

the period of the function may be practically two times the wavelength spacing between a wavelength belonging to the first group and a wavelength belonging to the second group. However, for the choice of the desired transfer function, the frequency should be considered as a parameter for periodicity, in place of the wavelength. By suitably choosing the number, the thickness and the orientation of the stack of the birefringent elements, it is possible to obtain practically any substantially frequency periodic transfer function. Techniques explained in the article of S.E. Harris et al., *"Optical Network Synthesis Using Birefringent Crystals.*I. Synthesis of Lossless Networks of Equal-Length Crystals"*, Journal of the Optical Society of America, vol.54, n.10 (1964) may be used in order to perform the synthesis of the birefringent elements for any arbitrarily prescribed transfer function. The prescribed transfer function, assumed to be periodic, is approximated by an exponential series containing a finite number of terms i. The number of birefringent elements corresponds to i-1: a higher number of elements allows to obtain a better approximation of the desired transfer function, in particular of the transition between the full-wave retarder behavior and the half-wave retarder behavior. More particularly, the lower the ratio between the maximum wavelength range needed for such transition and the period of the chosen periodic function, the higher the number of needed elements. In practice, a stack comprising at least five elements is preferred for most applications. More preferably, the stack may comprise at least ten elements. In order to find the orientation of the elements, a Fourier transform of the approximated function is performed. The thickness t of each birefringent element may be found by the following formula:

$$t = \frac{c}{A\Delta n}$$

wherein c is the speed of light, A is the frequency period of the chosen function and Δn is the birefringence. Thus, a low birefringence and/or a low period of the transfer function may lead to a higher thickness of the elements. For example, for a spacing of 100 GHz between interleaved channels in a bidirectional system, the period of the transfer function should be 200 GHz. With a birefringence of 0.1 an element thickness of 15 mm is found with the above formula. With a period of 4

THz (roughly corresponding to the C-band of an erbium doped fiber amplifier, i.e. 1530 nm - 1560 nm) and a birefringence of $5 \cdot 10^{-2}$, a thickness of 1.5 mm is found.

The number and the thickness of the birefringent elements may be preferably set so as to keep the overall attenuation introduced by the stack of birefringent elements lower than 0.5 dB, more preferably lower than or equal to 0.2 dB for both the first and the second group of wavelengths. A lower thickness of the birefringent elements allows to obtain a lower attenuation and a compact device. Preferably, in order to obtain a low element thickness, a birefringence of the element material higher than or equal to $1 \cdot 10^{-2}$ may be used. More preferably, a birefringence higher than or equal to $5 \cdot 10^{-2}$ may be used. Typical birefringent materials suitable for manufacturing birefringent waveplates suitable for the stack are mica, quartz, lithium niobate, barium titanate, calcite or sodium nitrate.

In order to overcome possible problems caused by thickness variation of the birefringent elements due to fabrication tolerances, the birefringent elements may be disposed so that a birefringent element having a thickness slightly lower than the calculated optimal thickness alternates to a birefringent element having a thickness slightly higher than the calculated optimal thickness. Alternatively, a substantially random distribution in thickness may be adopted. In any case, a systematic error in the thickness of the birefringent elements with respect to the calculated optimal thickness value should be avoided, in order to obtain the desired transition between the full-wave retardation behavior and the half-wave retardation behavior, in particular for applications in which such transition should be obtained in a small wavelength range. For applications in a wavelength range around 1550 nm, a systematic error of 1% with respect to the calculated optimal thickness may lead to a shift of the transition between full-wave and half-wave behavior of about ±15 nm, that may be unacceptable for some applications.

The bidirectional isolator according to the invention may be used in a bidirectional optical system, i.e., in an optical system in which a first group of signals having a first group of wavelengths is used for transmitting information in a forward direction (east to west) and a second group of signals having a second group of wavelengths is used for transmitting information in a backward direction (west to east). Typically, the bidirectional isolator may be used in an optical amplifier.

Fig.3 schematically shows a preferred embodiment of a bidirectional optical amplifier 30 using bidirectional isolators according to the invention. The bidirectional amplifier 30 comprises at least one optical amplifying medium 31 and a pumping system suitable for furnishing a pumping power and for providing such pumping power to the optical amplifying medium. In the exemplary embodiment of fig.3, the amplifying medium 31 may be a rare-earth doped optical fiber, e.g. an erbium-doped optical fiber, and the pumping system includes a first pump laser 32a and a first WDM coupler 33a. The rare-earth doped fiber 31 is connected to a first port of the WDM coupler 33a and the pump laser 32a is connected to a second port of the WDM coupler 33a. Preferably, the optical amplifier 30 also comprises a second pump laser 32b and a second WDM coupler 33b. At least one bidirectional isolator 34a according to the invention may be included in the optical amplifier 30. Preferably, a second bidirectional isolator 34b according to the invention may be included in the optical amplifier 30.

In operation, a first group of signals having wavelengths comprised in a first group of wavelengths propagates in a forward direction and a second group of signals having wavelengths comprised in a second group of wavelengths propagates in a backward direction through the rare-earth doped fiber. Typically, the first and the second group of wavelengths are comprised in a range around 1550 nm. First and second group of wavelengths may be comprised in mutually exclusive wavelength ranges. For example, the first group of signals may have a wavelength lower than or equal to 1565 nm. Preferably, the first group of signals may have a wavelength higher than or equal to 1545 nm. The second group of signals may have a wavelength higher than or equal to 1525 nm. Preferably, the second group of signals may have a wavelength lower than or equal to 1535 nm. Alternatively, the wavelengths of the first group of signals may be interleaved to the wavelengths of the second group of signals. The pump lasers 32a and 32b furnish pumping radiation suitable for amplifying the signal radiation of the first and the second group of wavelengths. Suitable pumping radiation for erbium-doped fibers may have a wavelength around 980 nm or around 1480 nm, or even higher wavelengths. Such pumping radiation is coupled into the rare-earth doped fiber 31 through the WDM couplers 33a, 33b, together with the signal radiation, i.e. both the first and the second group of signals. The bidirectional isolator 34a (or isolators 34a, 34b) allows the propagation of the first group of signals in forward direction

and the propagation of the second group of signals in backward direction. At the same time, the bidirectional isolator 34a (or isolators 34a, 34b) blocks back-reflected radiation having wavelength comprised in the first group of wavelengths propagating in backward direction and back-reflected radiation having wavelength comprised in the second group of wavelengths propagating in forward direction.

This advantageously avoids the accomplishment of different optical fiber paths for the different groups of wavelengths.

In another application, the bidirectional isolator according to the invention may be used in a multiple stage optical amplifier exploiting counter-propagating pump radiation, i.e., an optical amplifier in which an optical signal to be amplified and an optical pumping radiation having a different wavelength with respect to the wavelength of the optical signal propagate in opposite directions through the amplifier.

For example, fig.4 schematically shows a preferred embodiment of an optical amplifier 40 exploiting counter-propagating pump radiation. Optical amplifier 40 comprises at least a first amplifying medium 41 and a second amplifying medium 42, at least one pump laser 43 and a coupler 44, suitable for coupling optical pumping radiation emitted by pump laser 43 into said second amplifying medium. For example, first and second amplifying media 41, 42 may be lengths of Raman-active optical fibers, i.e. fibers capable of obtaining a gain by the Raman effect, so as they may be exploited for amplifying an optical signal propagating therethrough. Typically, such Raman-active fibers may be silica-based fibers. Typically, such silica-based fibers have a core comprising germania or another dopant suitable for enhancing the Raman effect inside the core. Preferably, the sum of the lengths of the Raman-active fibers may be lower than or equal to about 10 km, more preferably lower than or equal to about 8 km. Typically, the optical signal to be amplified may use one or more wavelengths comprised in a range around 1550 nm. Preferably, the optical signal may use one or more wavelengths higher than or equal to 1525 nm. Preferably, the optical signal may use one or more wavelengths lower than or equal to 1630 nm. For the purpose of Raman amplification of an optical signal having wavelength comprised in the specified range in silica-based fibers, a pump radiation having a wavelength lower than or equal to 1510 nm may be used. Preferably, such pump radiation may have a wavelength higher than or

equal o 1410 nm. Multiple pump lasers, even suitable for emitting pump radiation at different wavelengths, may be used. In another example, first and second amplifying media 41, 42 may be rare-earth doped optical fibers, e.g., erbium doped fibers. For amplification of an optical signal using one or more wavelengths in the range above specified a pumping radiation having a wavelength around 1480 nm may be exemplarily used.

Coming back to fig.4, the optical amplifier 40 is suitable for amplifying optical signal using one or more wavelengths λ_s, propagating in a forward direction. The wavelength or wavelengths of the optical signal to be amplified are in a first wavelength range. The pumping radiation emitted by the pump laser or lasers 43, typically comprising a continuous wave signal, has one or more wavelengths λ_p, propagating in the amplifying media 41, 42 in a backward direction. For this purpose, the output end of the second amplifying medium 42 is connected to a first port of the coupler 44, e.g., a WDM coupler, whereas the pump laser or lasers 43 is/are connected to a second port of the coupler 44. The wavelength or wavelengths of the pump radiation are in a second wavelength range, non-overlapping with the first wavelength range.

A bidirectional isolator 45 according to the invention is disposed between the first amplifying medium 41 and the second amplifying medium 42. The bidirectional isolator 45 allows propagation in a forward direction of wavelengths λ_s comprised in the first wavelength range and propagation in a backward direction of wavelengths λ_p comprised in the second wavelength range. That is, the bidirectional isolator 45 allows the propagation of the counter-propagating pump radiation from the second amplifying medium 42 to the first amplifying medium 41, with no necessity of using a suitable shunting circuit for allowing the pump radiation to by-pass the isolator. At the same time, the bidirectional isolator blocks back-reflected signal having wavelength or wavelengths comprised in the first wavelength range propagating in backward direction, and back-reflected pump radiation having wavelength or wavelengths comprised in the second wavelength range propagating in forward direction. In order to increase isolation of the optical signal, at least one unidirectional optical isolator may be further added. In the exemplary embodiment disclosed in fig.4, two unidirectional isolators 46, 47 are disposed at the ends of the amplifier 40.

Example 1

The Applicant has determined the structure of a stack of birefringent waveplates (number of waveplates, thickness, orientation) to be included in the bidirectional isolator of fig.1 in order to allow the propagation of a first group of signals having wavelengths comprised in a first wavelength range between 1410 nm and 1510 nm in one direction and the propagation of a second group of signals having wavelengths comprised in a second wavelength range between 1530 nm and 1630 nm in the opposite direction. Such bidirectional isolator may comply with the requirements for a double stage lumped Raman amplifier, according to the embodiment above described with reference to fig.4.

According to what stated above, the stack of birefringent waveplates should be arranged so as to obtain a half-wave retardation in one wavelength range, for example between 1410 nm and 1510 nm, and a full-wave retardation in the other wavelength range, i.e. between 1530 nm and 1630 nm. A tool was developed following the teachings of the above cited article of Harris et al. in order to determine a suitable stack structure. In order to keep the number of waveplates sufficiently low and at the same time for obtaining a better squared profile (maximum transfer function in the whole first wavelength range, minimum transfer function in the whole second wavelength range), the Fourier coefficients of the Fourier transform were multiplied by a weight function: this allowed to substantially eliminate ripples in the transfer function due to the low number of Fourier coefficients used for the approximation of the function. By setting a material birefringence Δn of $5 \cdot 10^{-2}$, it was found that fifteen birefringent waveplates having a thickness of 174.5 μm may be used for the purpose. Fig.5a shows the orientation ρ to be applied to each birefringent waveplate. The orientation is measured with respect to a horizontal polarization direction, rotation clockwise corresponding to positive angles. As it can be seen, the angle ρ oscillates around a value of 90° (vertical polarization direction) with progressively damped oscillations. Fig.5b shows the transfer function of the stack of birefringent waveplates disposed with orientations according to fig.5a. More particularly, fig.5b shows the normalized transmission T versus wavelength that can be obtained by sandwiching the stack of waveplates between two polarizers having crossed polarization directions. As it can be seen, the transmissivity is maximum between 1410 and 1510 nm, for which

the stack of waveplates behaves as a half-wave retarder, so that the polarization of an optical signal having wavelength comprised in such wavelength range is rotated of 90°. On the contrary, the transmissivity is minimum between 1530 and 1625 nm, for which the stack of waveplates behaves as a full-wave retarder, so that the polarization of an optical signal having wavelength comprised in such wavelength range is left unchanged. It is important to notice that the transmissivity value of the stack of waveplates passes from a maximum one to a minimum one in about 20 nm. This value or a lower one may be for example a requirement for an application of the stack of waveplates in a bidirectional isolator to be included in a double stage lumped Raman amplifier, in order to exploit as much as possible the signal wavelength range and the pump wavelength range. The Applicant has further evaluated that the attenuation introduced by such stack of waveplates may be lower than 0.5 dB in the wavelength range between 1525 and 1630 nm and lower than 0.1 dB in the wavelength range between 1410 and 1510 nm, if typical birefringent materials are used, such as mica or quartz.

Example 2

It was found that a critical parameter that may be carefully controlled in order to guarantee the desired transfer function is the thickness of the birefringent waveplates. Fig.6 shows how the plot of fig.5b may modify its profile if the thickness of the waveplates changes from 174.5 μm to 175.5 μm, for example due to an error in the fabrication of the waveplates. As it can be seen, the curve may shift towards higher wavelength values, so that the stack of waveplates may not perform as required in the boundary wavelength region between the first and the second wavelength range. In order to overcome such problem, and to take into account of possible variations of the thickness of the waveplates, for example due to fabrication tolerances, the Applicant has considered stacks of waveplates having slightly different thickness. It has been found that it is possible to reduce the variation of the transfer function due to variation of the thickness by avoiding a systematic error in the thickness of the waveplates with respect to the thickness value determined by the project tool (project value). Very reduced variation may be obtained:

a) with a stack of waveplates having a substantially random thickness variation around the project value;

b) with a stack of waveplates obtained by alternating a waveplate having a thickness lower than the project value to a waveplate having a thickness higher than the project value.

Fig.7 shows the two transfer functions obtained with the arrangements according to a) (dotted line 71) and b) (dashed line 72) compared with the "exact" transfer function obtained with the stack of waveplates described with reference to example 1 (continuous line 70). For the plots of fig.7, a random thickness value comprised between ±1 μm around the project value of 174.5 μm was considered for case a), and an alternation of waveplates having a thickness of 173.5 μm and 175.5 μm was considered for case b). As it can be seen, a very reduced variation of the transfer function can be obtained.

CLAIMS

1. An optical isolating device, adapted for allowing passage of a first group of optical signals having a first group of wavelengths in a first direction and for blocking passage of said first group of optical signals in a second direction, opposite to said first direction, and adapted for allowing passage of a second group of optical signals having a second group of wavelengths in said second direction and for blocking passage of said second group of optical signals in said first direction, said optical isolating device comprising:

   - first and second polarizers;
   - a nonreciprocal polarization rotator, arranged for rotating a polarization of a signal of substantially $45° \pm k \cdot 90°$, wherein k is a non-negative integer, in both said first and second directions;
   - a reciprocal polarization rotator;

   characterized in that

   - said reciprocal polarization rotator comprises a plurality of birefringent elements, having substantially the same thickness and being oriented so as to obtain a half wave retardation for said first group of signals and a full wave retardation for said second group of signals.

2. An optical isolating device according to claim 1, characterized in that said first group and said second group of signals have wavelengths included in mutually exclusive wavelength ranges.

3. An optical isolating device according to claim 2, characterized in that said first group of signals have wavelengths higher than or equal to 1525 nm.

4. An optical isolating device according to claim 3, characterized in that said first group of signals have wavelengths lower than or equal to 1630 nm.

5. An optical isolating device according to any one of claims 3 or 4, characterized in that said second group of signals have wavelengths lower than or equal to 1510 nm.

6. An optical isolating device according to claim 5, characterized in that said second group of signals have wavelengths higher than or equal to 1410 nm.

7. An optical isolating device according to claim 2, characterized in that said first group of signals have wavelengths higher than or equal to 1545 nm.

8. An optical isolating device according to claim 7, characterized in that said first group of signals have wavelengths lower than or equal to 1565 nm.

9. An optical isolating device according to any one of claims 7 or 8, characterized in that said second group of signals have wavelengths lower than or equal to 1535 nm.

10. An optical isolating device according to claim 9, characterized in that said second group of signals have wavelengths higher than or equal to 1525 nm.

11. An optical isolating device according to claim 1, characterized in that said first group and said second group of signals have interleaved wavelengths.

12. An optical isolating device according to any one of the preceding claims, characterized in that said birefringent elements have a thickness variation of less than or equal to 1%.

13. An optical isolating device according to any one of the preceding claims, characterized in that said plurality of birefringent elements are disposed so that elements having a lower thickness alternate to elements having a higher thickness.

14. An optical isolating device according to any one of the preceding claims, characterized in that said birefringent elements comprise a material having a birefringence higher than or equal to $1 \cdot 10^{-2}$.

15. An optical isolating device according to any one of the preceding claims, characterized in that said plurality of birefringent elements introduces an overall attenuation lower than 0.5 dB on both said first and second group of signals.

16. An optical amplifier comprising:

- at least a first optical amplifying medium;
- a pumping system suitable for furnishing a pumping power and for providing such pumping power to said first optical amplifying medium;
- an optical isolating device according to claim 1.

17. An optical amplifier according to claim 16, characterized in that said first optical amplifying medium comprises a rare-earth doped fiber and said pumping system comprises at least one pump laser and at least one WDM coupler, one end of said rare-earth doped fiber being connected to a first port of said WDM coupler and said pump laser being connected to a second port of said WDM coupler.

18. An optical amplifier according to claim 16, characterized in that it further comprises at least a second optical amplifying medium, said pumping system being suitable for providing said pumping power also to said second amplifying medium, said optical isolating device being disposed between said first and second amplifying medium.

19. An optical amplifier according to claim 18, said optical amplifier being suitable for transmitting said first group of signals in said first direction, characterized in that:

    - said first optical amplifying medium comprises a first length of Raman-active optical fiber;
    - said second optical amplifying medium comprises a second length of Raman-active optical fiber, downstream from said first length of Raman-active optical fiber with respect to said first direction;
    - said pumping system comprises at least one pump laser adapted for emitting a pumping radiation having a wavelength included in said second group of wavelengths, said pumping radiation being adapted for causing Raman amplification of said first group of signals in said first and said second lengths of Raman-active optical fiber;

- said pumping system further comprises at least one WDM coupler, one end of said second length of Raman-active fiber being optically connected to a first port of said WDM coupler and said at least one pump laser being optically connected to a second port of said WDM coupler, so that said pumping radiation may propagate from said second length of Raman-active optical fiber to said first length of Raman-active optical fiber.

20. An optical communication line comprising a length of optical transmission fiber and an optical isolating device according to any one of claims 1 to 15 optically coupled along said optical transmission fiber.

21. An optical communication line comprising a length of optical transmission fiber and an optical amplifier according to any one of claims 16 to 19 optically coupled along said optical transmission fiber.

22. An optical communication system comprising an optical communication line according to any one of claims 20 or 21, at least a first optical transmitter apt to transmit at least one optical signal of said first group of optical signals into one end of said optical communication line in said first direction and at least one optical receiver apt to receive said at least one optical signal from an opposite end of said optical communication line.

ABSTRACT

An optical isolating device, adapted for allowing passage of a first group of optical signals having a first group of wavelengths in a first direction and for blocking passage of said first group of optical signals in a second direction, opposite to said first direction, and adapted for allowing passage of a second group of optical signals having a second group of wavelengths in said second direction and for blocking passage of said second group of optical signals in said first direction. The optical isolating device comprises: first and second polarization beam splitters; a nonreciprocal polarization rotator; a reciprocal polarization rotator. The reciprocal polarization rotator comprises a plurality of birefringent elements, having substantially the same thickness and being oriented with each other so as to obtain a half wave retardation for said first group of signals and a full wave retardation for said second group of signals.

Fig.1

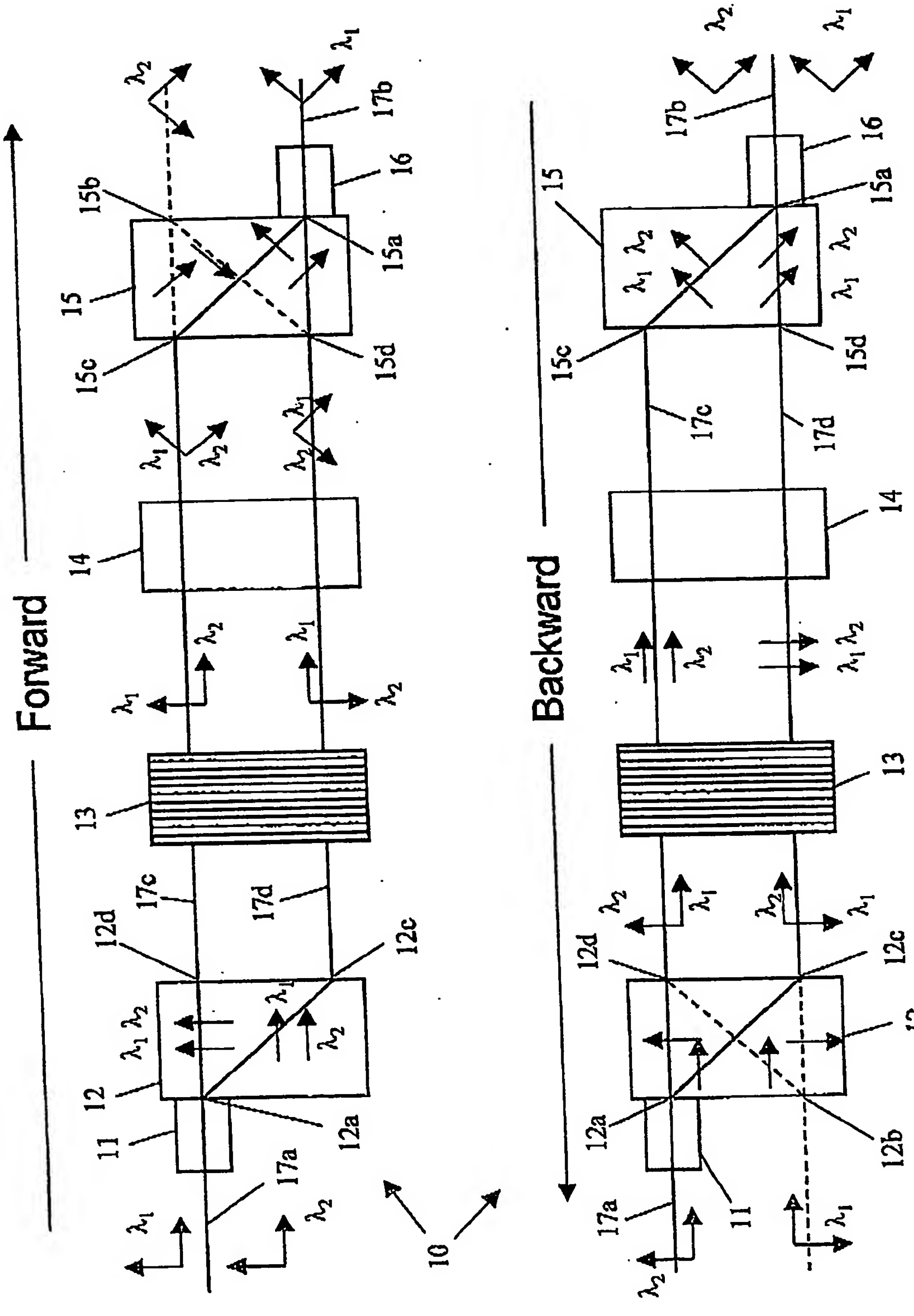

Forward
Backward
10
11
12
12a
12b
12c
12d
13
14
15
15a
15b
15c
15d
16
17a
17b
17c
17d
λ_1
λ_2

Fig.1

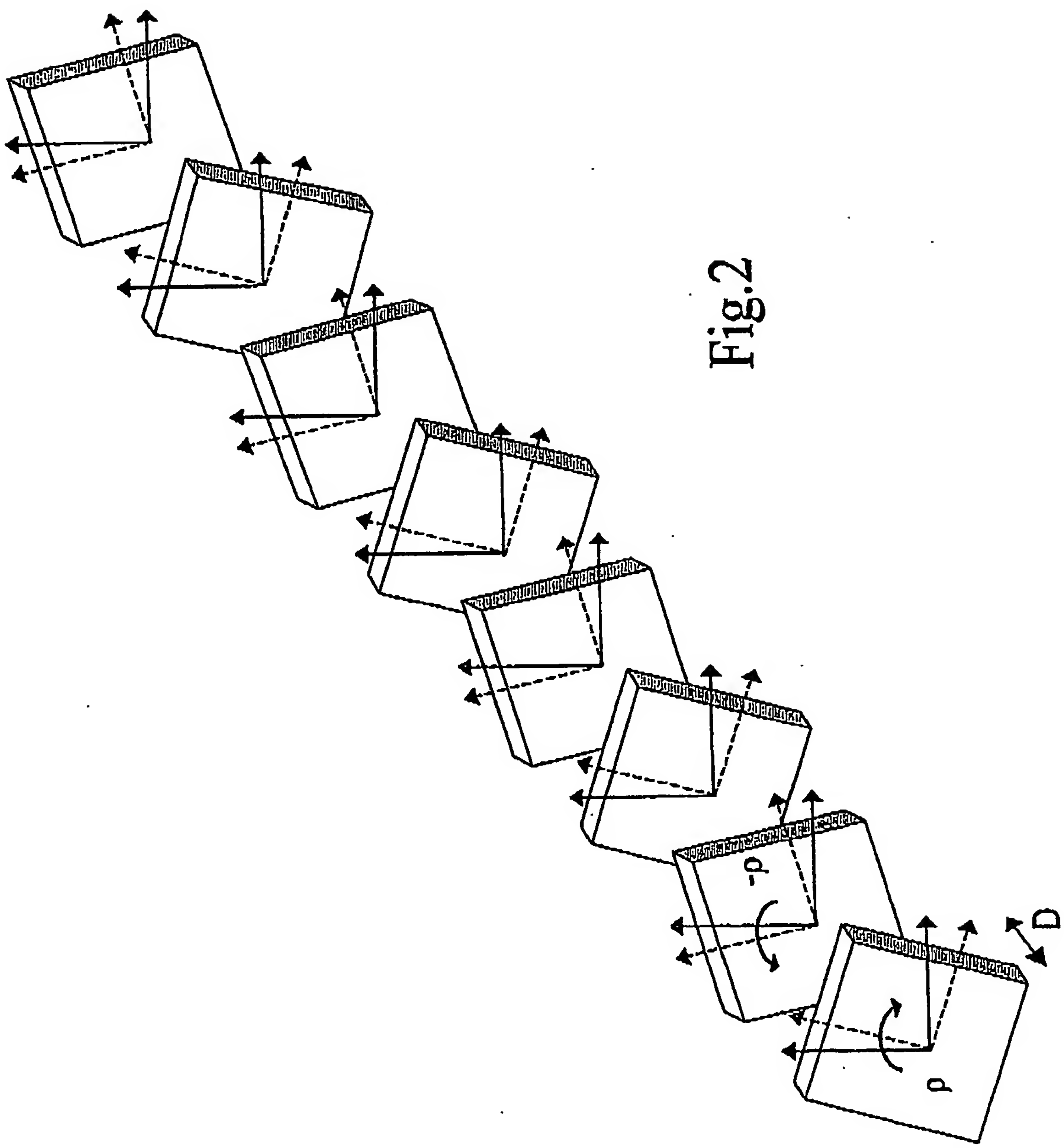


Fig.2

PC0981

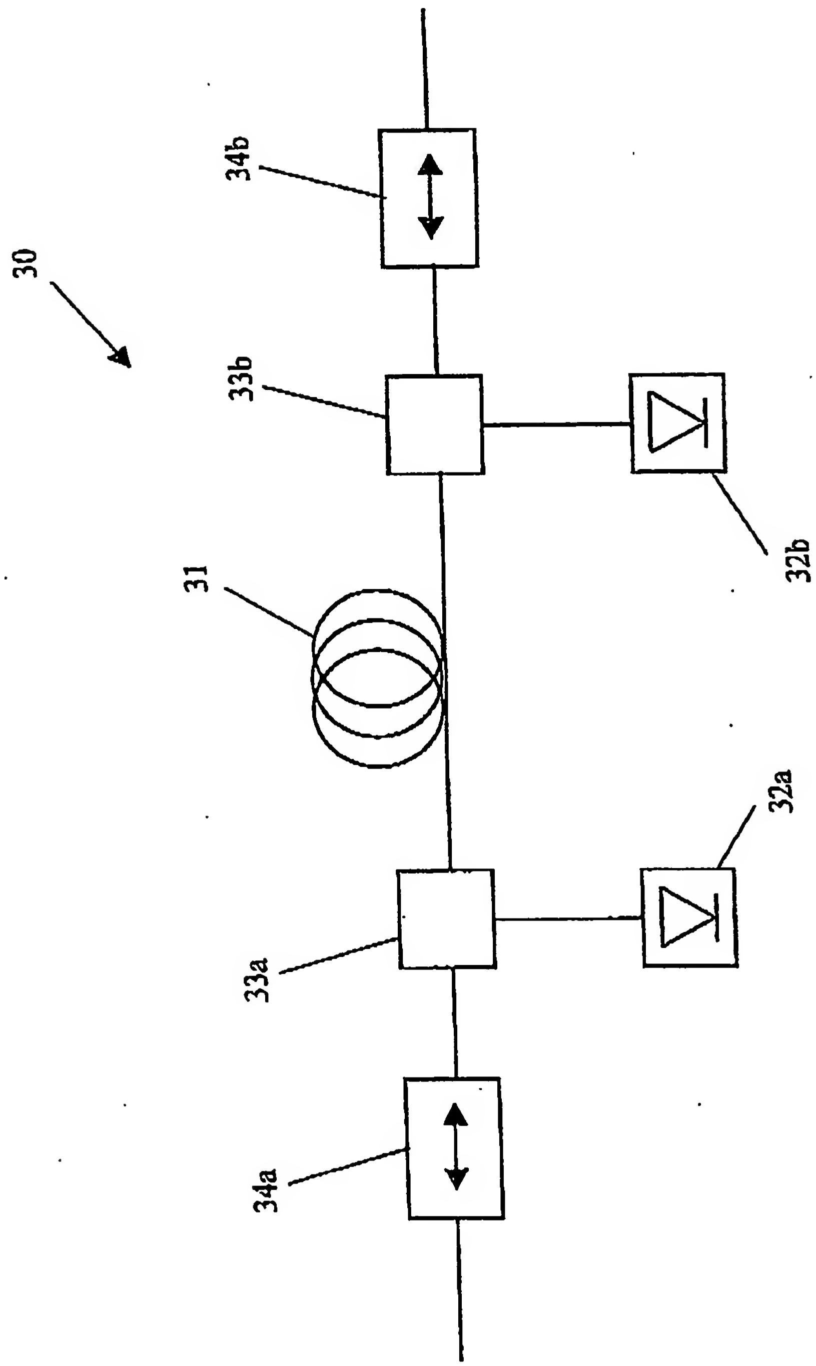


Fig.3

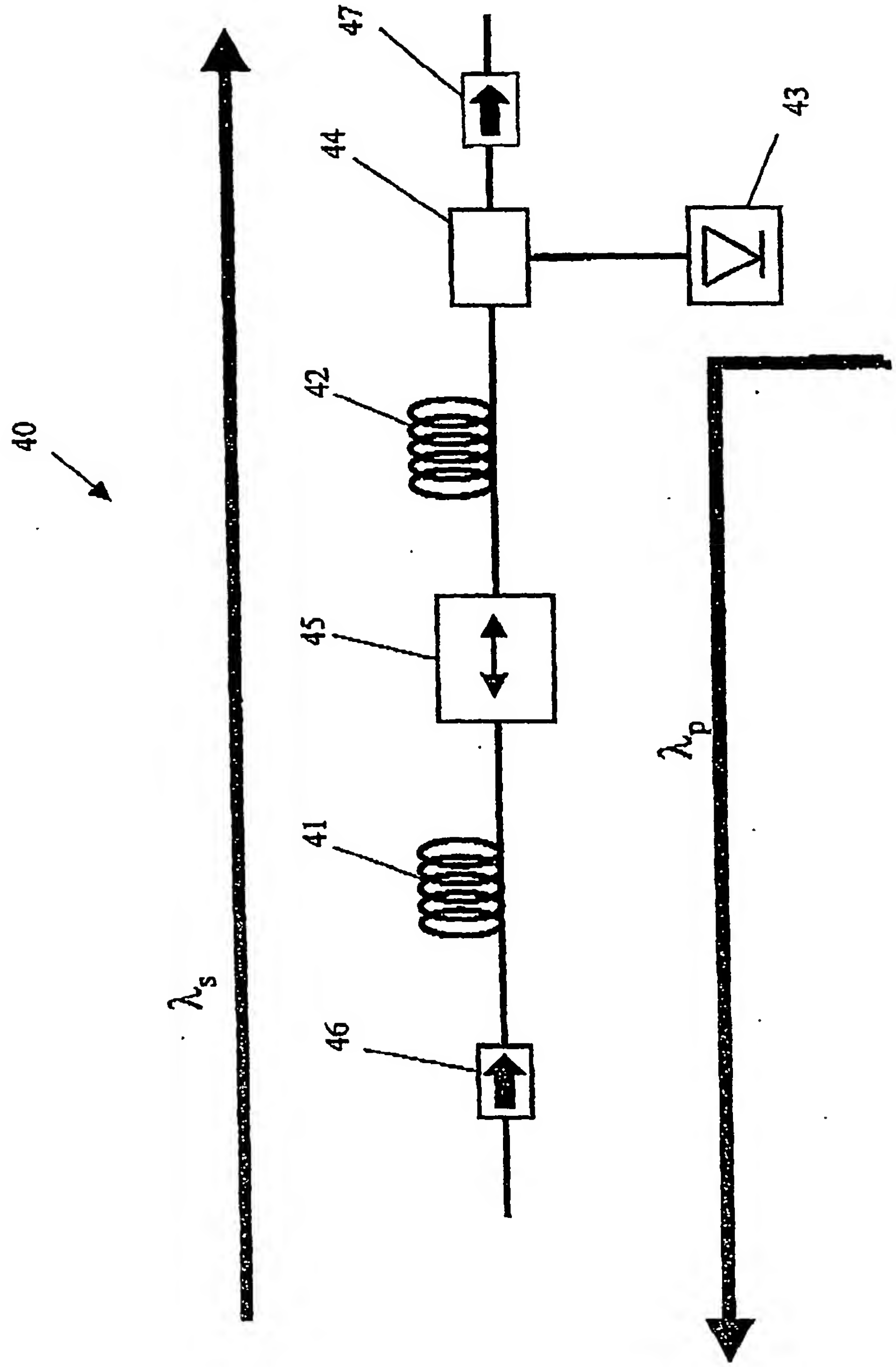


Fig.4

PC0981

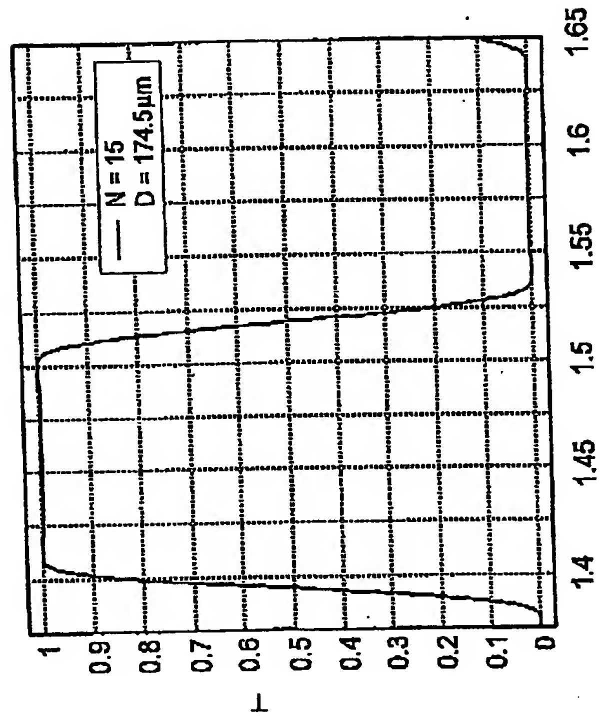


Fig.5b

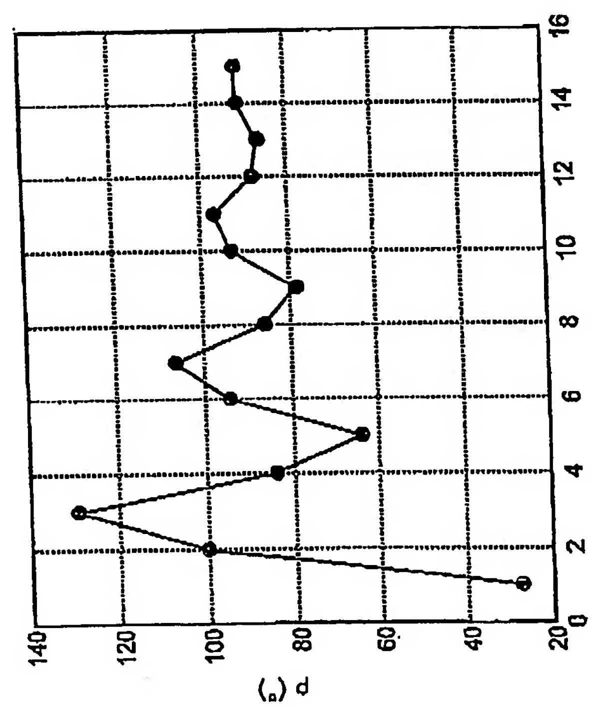
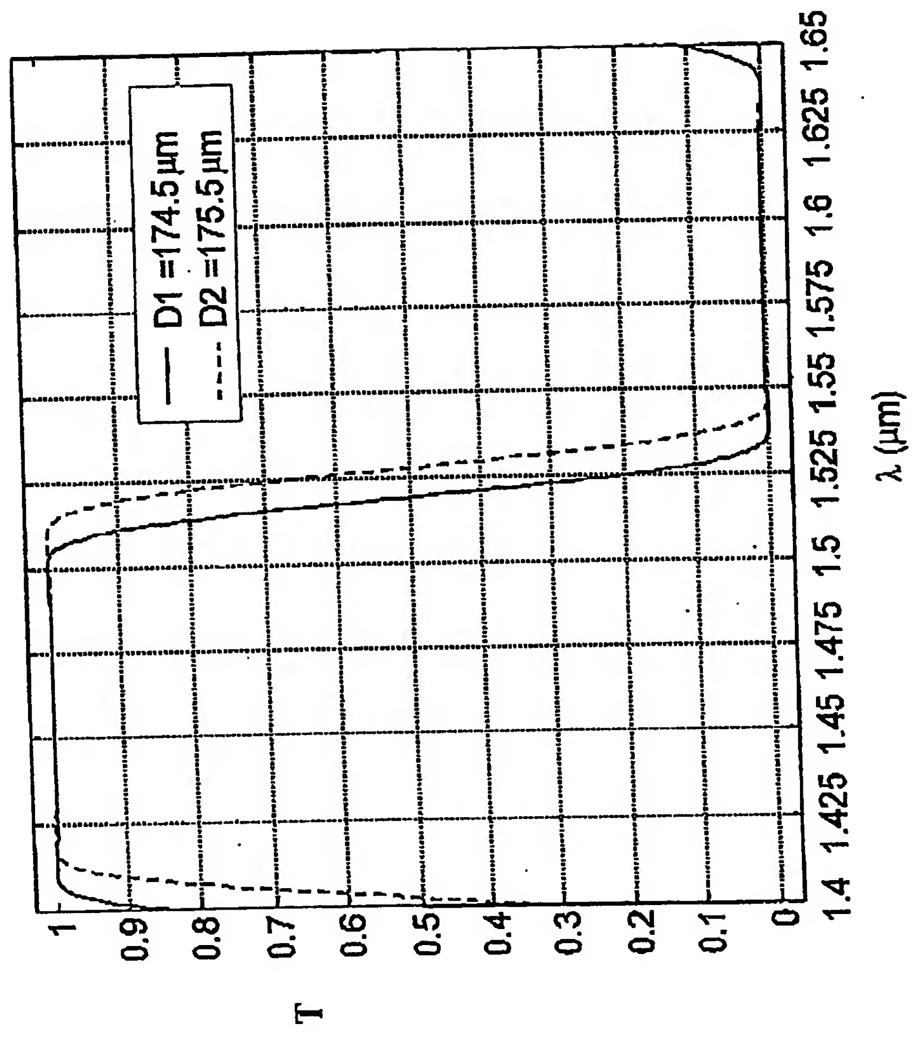


Fig.5a

PC0981



D1 =174.5µm
D2 =175.5µm
T
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.4 1.425 1.45 1.475 1.5 1.525 1.55 1.575 1.6 1.625 1.65
λ (µm)

Fig.6

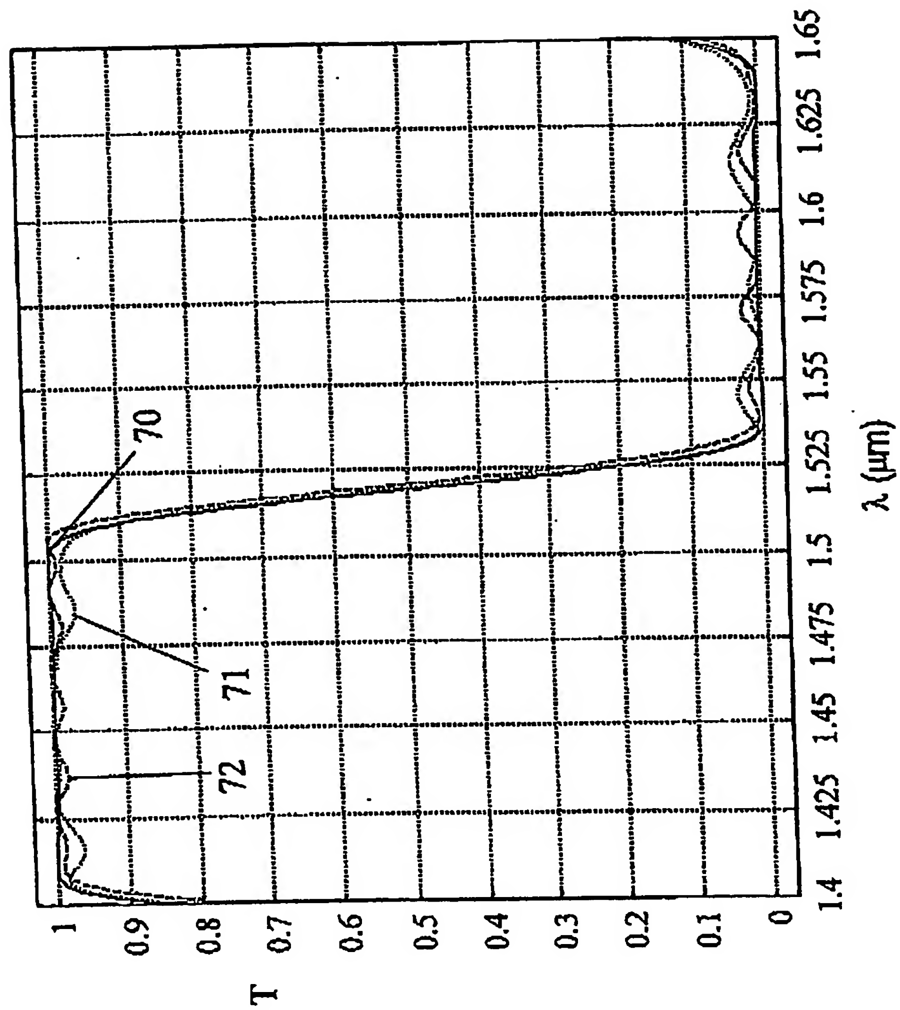

T
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1.4
1.425
1.45
1.475
1.5
1.525
1.55
1.575
1.6
1.625
1.65
λ (μm)
70
71
72

Fig.7